SOIL TEMPERATURE GRADIENTS ON THE ISLAND OF HAWAII

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PURPOSE

The primary purpose of this study was to measure and analyze soil temperatures at nine sites that reflect the dominant climatic areas of the Island of Hawaii. Six of these sites, approximating a dry to wet transect line, are summarized. Another purpose was to verify the measured data with the hypothesized soil temperature regime to support the ongoing soil survey. A third purpose was to identify lapse rates for soil temperature along a transect line that runs from the dry desert in northwest Hawaii, across Mauna Kea, and down to the wet sites near Hilo.

PREVIOUS CLIMATE RESEARCH ON HAWAII

Juvik and Nullet (1994) showed that annual variation in average monthly air temperature was quite small at each of four sites in Hawaii (5-6ºC). For the period of record covered (1992-1993), the range of average daily, maximum, and minimum temperatures remained fairly constant with elevation. The lapse rate of MAAT equates to 6.5ºC per 1000 meters (3.6ºF per 1000 feet). Soil temperatures follow a somewhat different pattern. The average range of soil temperature at 1 cm is less than the average of air temperature at the two lower sites but greater at the upper site by 1ºC.

Juvik and Juvik (1998) noted that Hawaii's climate is notable for its low day-to-day and month-to-month variability. The annual variability in mean monthly temperatures at sea level is only about 5ºC (9ºF). A trade wind inversion exists on Hawaii at an elevation around 1800 meters. This is verified with measurements transmitted from balloon-borne instruments launched twice daily by the National Weather service from Hilo, Hawaii, and Lihue, Kauai, airports. Currently, the lapse rate decreases at 6.5ºC per 1000 m (3.6ºF per 1000 ft) to an elevation of 1500 meters. Thereafter, the lapse rates fall less rapidly to about 4.0ºC per 1000 m.

From 1975 to 1998, soil temperature regimes were designated as "Iso" with less than 5°C (9°F) difference between average summer and winter soil temperatures at a 50-cm depth (Soil Survey Staff, 1975). During the 1980s, research from a climate monitoring network on Haleakala (a mountain on the island of Maui) had shown that 3 out of 19 stations differed more than 5°C at 50 cm which placed these sites as Hyperthermic (D. Nullet, et al., 1990). As a result of this study, the "iso" definition in Soil Taxonomy was amended to allow isotivity values to range to 6ºC (Soil Survey Staff, 1998).

STUDY AREA

The Big Island of Hawaii is located in the tropics, the zone between the Tropic of Cancer and the Tropic of Capricorn. Hawaii is between 18° and 21° north of the equator and is about 155° west of the Prime Meridian (Figure 1).

Big Island, with a surface area of only 10,455 km^2 (4035 mi^2), exhibits a wide range of climatic diversity comparable with that found on continents. The three major factors that contribute to this climatic diversity are topographic relief (0 to 4205 m elevation), a large-scale synoptic wind field, and a local circulation resulting from differential heating and cooling of the land, water, mountain, and lowland areas. Above the 3200-meter (10,500-feet) level on Mauna Kea and Mauna Loa volcanoes, all months have mean air temperature below 10ºC (50ºF) and the climates are classified as periglacial (Figure 2). Nighttime freezing is common throughout the year (Juvik, et al., 1978).

The mean annual precipitation at the six sites varies from 250 mm at the Kawaihae site to over 5400 mm at the rain forest site near Hilo (Juvik, et al., 1992). Land use is range at the Kawaihae site, pasture at the Parker HQ and Hanaipoe sites, forest and macadamia nuts at the Hamakua sites, and barren glacial mountain land at the Mauna Kea site. The soil at the Mauna Kea site developed in glaciated volcanic material that has been sorted through frost action. The resulting soil is a cobble pavement overlying sand. The soils at the other sites developed in volcanic ash (Figure 3). Additional site characteristics are presented in Table 1.

MATERIALS AND METHODS

The StowAway temperature loggers used in this study store a maximum of 1800 data points during periods ranging from 15 minutes to 360 days. These loggers are manufactured by OnSet Corporation and are used in many NRCS studies for consistent comparisons of temperature. Prior to installation, these loggers were programmed to collect data every 4 hours and 48 minutes for 360 days. This frequency is the same as five times each day. Their certified temperature accuracy is ±0.7°F (±0.4°C). At each site, a 23-cm (9-in) PVC pipe with a 10-cm (4-in) diameter housed three StowAway temperature loggers and a desiccant pack to absorb excess moisture. Holes drilled in the PVC pipe allowed 1.8-m (6-ft) sensor leads to exit outside while the temperature loggers were protected from the weather elements. A high-grade sealant was applied to the caps of the units to prevent water from entering. Site installation was initiated by digging a hole to a depth of 50 cm (20 in). Site data were collected and the soils briefly examined to gather a taxonomic classification. One temperature sensor lead was tied to a bush or sapling at five sites to capture air temperature and generally placed from 0.9 to 1.2 m (3 to 4 ft) above the soil surface. Care was taken to position the sensor so that it was never exposed to direct sunlight and it had a free flow of air around it. Two soil temperature sensor leads were installed at each site -- one at the 10-cm (4-in) soil depth and one at the 50-cm (20-in) soil depth. Due to a lack of suitable vegetation, a third soil sensor was added at 20 cm for the Kawaihae and the Mauna Kea sites. Finally, the PVC pipe was buried at about 10 cm and covered with soil. All of the sites were installed during early February 1998.

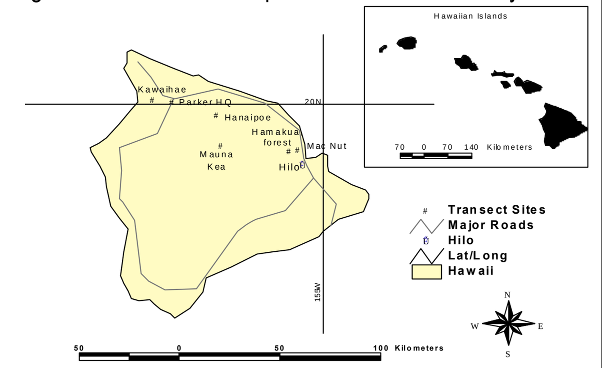
RESULTS

Mean Annual Soil Temperature (MAST)

Monthly and annual summaries for the 50-cm soil depth are shown in Table 2. According to criteria listed in *Soil Taxonomy*, these data show the Kawaihae site is Isohyperthermic, the Parker HQ site and the Hamakua forest and Mac nut sites are Isothermic, the Hanaipoe site is Isomesic, and the Mauna Kea site is Mesic (Soil Survey Staff, 1998). The temperature gradient from Kawaihae to the Parker HQ site is quite sharp. It is only 8.9 km between these sites but the MAST drops 8.2°C. This equates to a 0.9ºC decrease in MAST for every 1000 meters distance between these two sites.

Except for the Mauna Kea site, temperature data for this study support the hypothesized soil temperature regimes. Long-term air temperature data from a weather station on Mauna Kea had suggested this site would be Frigid or perhaps Isofrigid (Meteorological Staff, 1983). Because air temperature could not be easily measured at the Mauna Kea study site, it is conjectured that the unvegetated soil surface accentuates the daily highs and suppresses the daily lows, resulting in a MAST at 10 cm, 20 cm, and 50 cm that is at least 6ºC warmer than the MAAT.

Figure 1. Location of temperature sites in the study area.



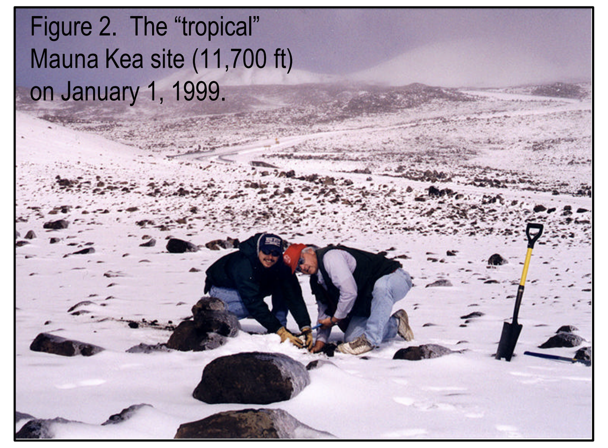


Figure 2. The "tropical" Mauna Kea site (11,700 ft) on January 1, 1999.

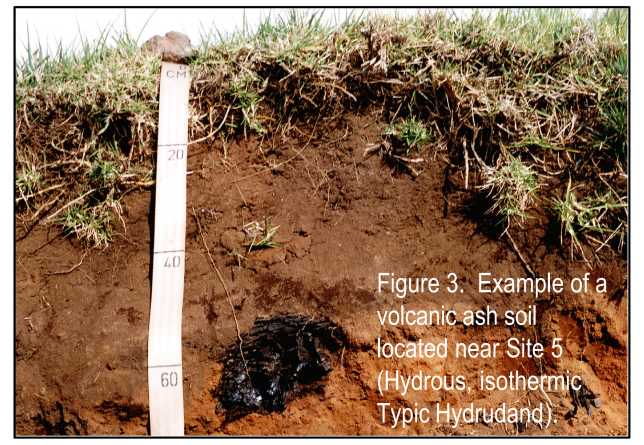


Figure 3. Example of a volcanic ash soil located near Site 5 (Hydrous, isothermic Typic Hydrudand).

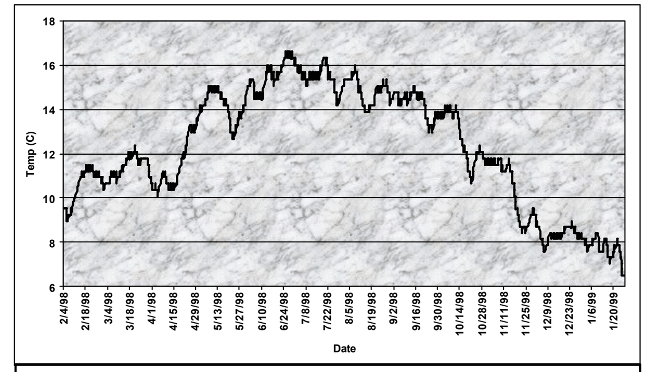


Figure 4. Temperature signature of the 50-cm soil depth on Mauna Kea.

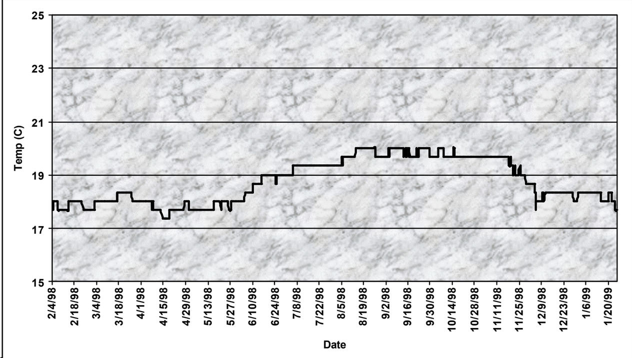


Figure 5. Temperature signature of the 50-cm soil depth at the Hamakua forest site.

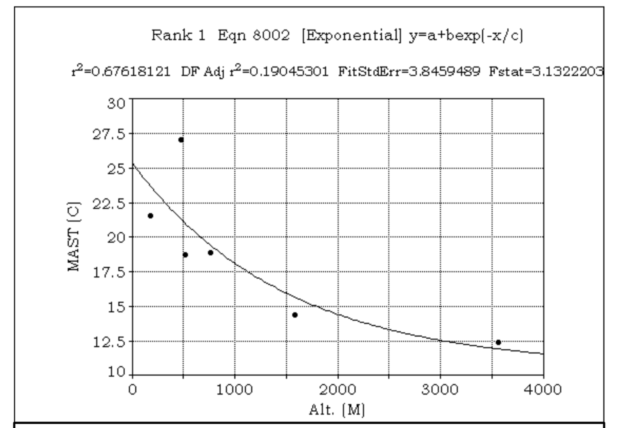


Figure 6. Regression analysis comparing MAST and altitude for sites on the Island of Hawaii.

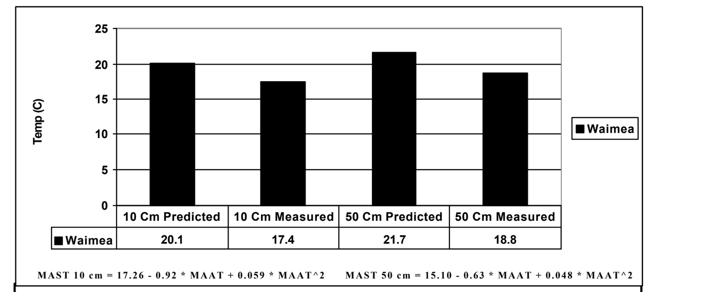


Figure 7. Comparison of predicted MAST and measured data from the Parker HQ site near Waimea, Hawaii.

Figure 8. South Point, Big Island -- Three additional soil temperature loggers were installed in this part of Hawaii during February 1999.

Table 1. Soil and Site Information for the Sites on Hawaii.

Site (Name)	Latitude (N)	Longitude (W)	Elevation (m)	Elevation (ft)	Slope (%)	Aspect (°)	Annual Precip. (mm)	Annual Precip. (in)
Kawaihae	20°01'26"	155°45'38"	472	1549	7	280	255	10
Parker HQ	20°00'37"	155°40'35"	764	2506	2	270	585	23
Hanaipoe	19°56'41"	155°28'30"	1585	5200	13	0	585	23
Mauna Kea	19°47'31"	155°27'26"	3566	11700	5	0	380	15
Hamakua Forest	19°46'01"	155°09'10"	518	1700	25	70	5460	215
Hamakua Mac Nut	19°46'13"	155°06'40"	183	600	5	90	4065	160

Table 3. Mean Annual Soil Temperature Lapse Rates Calculated from Measured Data.

Site Names (Transect ID and Moisture)	Altitude Change (m)	Decrease in Lapse Rate (°C / 1000 m)
Kawaihae to Parker HQ -- Dry	292	28.1
Parker HQ to Hanaipoe -- Dry	821	5.5
Hanaipoe to Mauna Kea -- Dry	1981	1.0
Kawaihae to Mauna Kea -- Dry	3094	4.7
Hamakua Mac Nut to Forest -- Wet	335	8.4
Hamakua Forest to Mauna Kea -- Wet to Dry	3048	2.1
Hamakua Mac Nut to Mauna Kea -- Wet to Dry	3383	2.7

Table 2. Monthly, Seasonal, and Annual Soil Temperature Averages for the 50-cm Soil Depth.

Analysis	Kawaihae (°C)	Parker HQ (°C)	Hanaipoe (°C)	Mauna Kea (°C)	Hamakua Forest (°C)	Hamakua Mac Nut (°C)
Jan	24.8	17.9	12.7	7.8	18.2	20.1
Feb	24.6	17.4	11.7	10.6	17.8	21.4
Mar	26.3	18.0	12.6	11.4	18.1	22.5
Apr	25.5	17.8	13.2	11.5	17.7	21.5
May	26.5	18.2	13.7	14.2	17.7	20.4
Jun	27.3	19.1	14.9	15.6	18.4	21.6
Jul	29.3	19.5	15.5	15.5	19.3	21.8
Aug	30.5	20.1	16.4	14.9	19.8	22.4
Sep	29.4	20.1	16.4	14.3	19.9	22.9
Oct	28.3	20.0	15.7	12.7	19.7	22.2
Nov	26.5	19.5	14.8	10.4	19.4	21.2
Dec	24.7	18.4	13.6	8.4	18.3	20.0
MAST	27.0	18.8	14.3	12.3	18.7	21.5
MST	29.0	19.6	15.6	15.3	19.2	21.9
MWT	24.7	17.9	12.6	8.9	18.1	20.5
MS-MW	4.4	1.7	3.0	6.4	1.1	1.4

RESULTS, cont.

Annual Soil Temperature Signature and Isotivity Values

The 50-cm depth on Mauna Kea also has a temperature signature that shows the most extreme seasonal variation of any site in the study (Figure 4). Here, the isotivity value is 6.4ºC, the largest in the study area (Table 2). Consequently, the soil at this site has a Mesic soil temperature regime (Soil Survey Staff, 1998).

The Mauna Kea site is contrasted by the temperature signature and the small isotivity value of the 50-cm depth at the Hamakua forest site northwest of Hilo (Figure 5 and Table 2). At 1.1ºC, the isotivity value at this site is the lowest for the study area.

However, we suggest that the definition of "iso" needs to be re-examined. The premise of "iso" is that the months of June, July, and August would have the highest soil temperature readings and December, January, and February would have the lowest soil temperature readings in the northern hemisphere (Soil Survey Staff, 1975). At the Hamakua forest site, this does not hold true. There is a two-month shift in the extreme temperatures. Consequently, the three warmest months for soil temperature at 50 cm are August, September, and October and the three coldest months are February, April, and May (Table 2). The difference between the average of the three coldest and the three warmest months is 2.1ºC, compared with 1.1°C using the standard method to determine isotivity. This supports the general climate of Hawaii where the warmest months are not June and July when the sun is the highest but August and September, and its coolest month, not December when the sun is farthest south and days are shortest, but February and March reflecting the seasonal lag in the ocean's temperature (Price, 1982).

Relationship of MAST to Altitude

For the tropics, it has been documented in a least two studies that MAST and altitude can have a high R^2. A ten-point transect study in the Caribbean National Forest (conducted by the U.S. Forest Service during 1985 and 1986) showed an R^2 of 0.93 between MAST and altitude (L. Huffaker, 1999). Embreachts and Tavernier (1986) reported an R^2 of 0.86 between MAST and altitude for a study in Cameroon, Africa, from 15 scattered sites within 10ºN of the Equator.

Regression analysis of MAST and altitude for the Hawaii sites is shown in Figure 6. The low R^2 value of 0.68 verifies that, in Hawaii, there is no precise mathematical model to accurately determine the MAST solely on the basis of altitude.

Relationship of MAST to MAAT

Smith, et al., (1964) cited that in humid oceanic climates when soils receive large amounts of annual rainfall, the MAST at 50 cm is reported to be cooler than the MAAT because of the lack of solar radiation or the effect of evaporation. This relationship does not hold true at the two Hamakua sites with high precipitation and low amounts of solar radiation northwest of Hilo.

In their work on Maui during the 1980s, Ikawa and Kourouma (1985) developed equations to calculate MAST from MAAT at both the 10-cm and 50-cm soil depths at relatively dry sites. Figure 7 displays the results of comparing measured data from the relatively dry location at the Parker HQ site in Waimea, Hawaii, with their equations. While the results are encouraging, it appears the equations to determine MAST work better on Maui.

Lapse Rates

The mean annual air temperature lapse rates, or the decrease in air temperature per 1000 meters rise in altitude, were calculated from two points on both the dry side and the wet side of Hawaii. The lapse rate from the Parker HQ site to the Hanaipoie Site on the dry side of Hawaii (6.3ºC) is nearly identical (6.5ºC) to that presented by Juvik and Juvik (1998). However, the wet Hamakua sites northwest of Hilo have a larger lapse rate at 9.7ºC than modeled by previous researchers. It is presumed that the rapid increase in the precipitation gradient with altitude contributes to the increase in the lapse rate.

Mean annual soil temperature (MAST) lapse rates for both the dry and wet side of Hawaii are shown in Table 3. The lapse rates have a larger range on the dry side (1.0ºC to 23.7ºC) than on the wet side (2.1ºC to 8.2ºC). From these measured data, it is concluded that one fixed MAST lapse rate will not work very well in Hawaii and is not worth pursuing as a research issue.

The relationship of the MAAT lapse rate to the MAST lapse rate was examined for a two-point transect line on both the dry side and the wet side. On the dry side, the lapse rate ratio of MAAT to MAST is 1.1:1 while it is 1.2:1 on the wet side. The ratios are similar and infer that the decrease in MAST with altitude will occur at a slower rate than the decrease in MAAT. In other words, changes in soil temperature with increasing altitude are not proportional to change in air temperature with increasing altitude.

SUMMARY AND DISCUSSION

An experienced field scientist can predict the soil temperature regimes at a specific location in Hawaii with a fair degree of accuracy. The measured soil temperature regimes agreed with field predictions at five of the six sites in this study. However, prediction of the exact MAST at an individual site is much more difficult. Many attempts have been devised to approximate MAST on the basis of MAAT, altitude, and lapse rates. Some studies in tropical environments have presented high R^2 values for their regression equations. Unfortunately, most of these studies reflect data from a specific ecosystem (Huffaker, 1998). When equations are taken from any one of these studies, they do not "fit" well with measured soil temperature data in Hawaii. Consequently, any "simple" mathematical model to predict MAST in Hawaii will simply not work.

With annual data from a minimum of 20 additional sites throughout Big Island, a better understanding of the MAST would evolve (Figure 8). It is suggested that a workable model to accurately predict MAST in Hawaii should integrate MAAT, altitude, slope percent and geometry, aspect, percent vegetative cover, and precipitation.

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